APPLICATION FOR UNITED STATES PATENT

REDUCED FOUR-WAVE MIXING RAMAN AMPLIFICATION ARCHITECTURE

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REDUCED FOUR-WAVE MIXING AND RAMAN AMPLIFICATION ARCHITECTURE

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STATEMENT OF RELATED APPLICATIONS

The present applications claims priority from U.S. Provisional App. No.

10   60/279,854, entitled INTERACTION OF FOUR-WAVE MIXING AND

DISTRIBUTED RAMAN ARCHITECTURE and filed on March 28, 2001 (attorney

docket no. CISCP690+). The contents of this provisional application are incorporated

herein by reference in their entirety.

15   ## BACKGROUND OF THE INVENTION

The present invention relates to optical communication systems and more

particularly to amplification in optical communication systems.

The explosion of communication services, ranging from video teleconferencing to

electronic commerce, has spawned a new era of personal and business interactions. As

20   evident in the rapid growth of Internet traffic, consumers and businesses have embraced

broadband services, viewing them as a necessity. However, this enormous growth in

traffic challenges the telecommunication industry to develop technology that will greatly

expand the bandwidth of existing communication systems. Further improvements in

optical communications hold great promise to meet continuing demands for greater and

25   greater bandwidth.

Wavelength Division Multiplexing (WDM) technology, in particular Dense

WDM (DWDM) techniques, permits the concurrent transmission of multiple channels

over a common optical fiber. The advent of Erbium Doped Fiber Amplifiers (EDFAs)

5   has accelerated the development of WDM systems by providing a cost-effective optical

amplifier that is transparent to data rate and format. An EDFA amplifies all the

wavelengths simultaneously, enabling the composite optical signals to travel large

distances (e.g., 600 km or greater) without regeneration.

One of the principal limitations of EDFA technology is limited bandwidth.

10   Discrete and distributed Raman amplifiers have been developed to overcome this

limitation. They provide very high gain across a wide range of wavelengths. Moreover,

discrete and distributed Raman amplifiers increase the distance between optical

regeneration points, while allowing closer channel spacing. The operation of Raman

amplifiers involves transmitting high-power laser pump energy down a fiber. The pump

15   energy amplifies the WDM signal.

The performance of Raman amplifiers in DWDM systems is limited by various

impairments. One such impairment is four-wave mixing, a common detriment to optical

communication system performance. If three wavelength components of a DWDM

signal located at the optical frequencies f_1, f_2, and f_3 are being amplified, non-linear

20   effects will cause generation of an undesired fourth component at $f_{fwm}=f_1+f_2-f_3$. This

undesired fourth component is a four-wave mixing product. The four-wave mixing

product represents a noise-like impairment that can affect reception of a WDM channel at

or near f_{fwm}.

Suppressing the generation of four-wave mixing products has been a key concern in the design of Raman amplifiers, both discrete and distributed. In particular, the desire to limit four-wave mixing effects has led Raman amplifier designers to inject pump

5   energy into a fiber exclusively in a counter-propagating direction relative to the propagation direction of the signal to be amplified. Unfortunately, such an approach also concentrates the amplification effects towards the end of the fiber, limiting the signal to noise ratio performance of the Raman amplifier.

What is needed are systems and methods for improving both four-wave mixing

10   product suppression and signal to noise ratio in Raman amplifiers.

SUMMARY OF THE INVENTION

Raman amplifiers with improved signal to noise ratio and four-wave mixing product suppression are provided by virtue of one embodiment of the present invention.

5 In one embodiment, both co-propagating and counter-propagating pump energy are employed to cause Raman amplification effects within a fiber. The resulting improved performance including improved four-wave mixing product suppression facilitates denser WDM channel spacings and/or longer distance transmission without regeneration of optical signals.

10 According to a first aspect of the present invention, apparatus for amplifying an optical signal includes: a fiber and an optical pump energy source disposed to inject optical pump energy into the fiber in a co-propagating direction relative to a transmission direction of an optical signal in the fiber to cause Raman amplification of the signal in accordance with a gain level. The gain level is greater than 4 dB.

15 According to a second aspect of the present invention, apparatus for amplifying an optical signal includes: a first optical pump energy source disposed to inject optical pump energy into a fiber in a co-propagating direction relative to a transmission direction of the optical signal to cause Raman amplification of the signal in accordance with a first gain level, and a second optical pump energy source disposed to inject optical pump

20 energy into the fiber in a counter-propagating direction relative to the transmission direction of the optical signal to cause Raman amplification of the signal in accordance with a second gain level. The optical signal experiences a total gain level includes the first gain level and the second gain level. The first gain level is greater than 4 dB.

Further understanding of the nature and advantages of the inventions herein may be realized by reference to the remaining portions of the specification and the attached drawings.

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BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 depicts an optical amplification architecture according to one embodiment of the present invention.

5   Fig. 2 depicts a first contour showing the tradeoff between per channel input power and forward Raman gain for a constant optical signal to noise ratio and a second contour showing the tradeoff between four wave mixing-induced crosstalk and forward Raman gain for a constant forward gain saturation according to one embodiment of the present invention.

10   Fig. 3 is a graph depicting the relationship between cross-gain modulation and gain saturation according to one embodiment of the present invention.

Fig. 4 is a graph depicting the relationship between double Rayleigh back-scattering and Raman gain according to one embodiment of the present invention.

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DESCRIPTION OF SPECIFIC EMBODIMENTS

One embodiment of the present invention is directed toward a Raman amplifier

5   configuration that employs both co-propagating and counter-propagating optical pumps.

The inventors have discovered that such a configuration may achieve a better

combination of four-wave mixing product suppression and amplifier output signal to

noise ratio than could be achieved with prior art systems employing a counter-

propagating optical pump signal alone. Previously, designers have either failed to take

10   advantage of co-propagating pump energy or used insufficient co-propagating pump

energy to realize the advantages attainable by embodiments of the present invention.

More particularly, a Raman amplifier according to the present invention

employing both counter-propagating and co-propagating optical pumps may achieve

greater four-wave mixing product suppression than a Raman amplifier using only a

15   counter-propagating pump to achieve the same gain and output signal to noise ratio.

Alternatively, a Raman amplifier according to the present invention may achieve a higher

output signal to noise ratio than a Raman amplifier using only a counter-propagating

pump to achieve the same gain and four-wave mixing product suppression.

Fig. 1 depicts an optical amplification architecture according to one embodiment

20   of the present invention. An optical link 100 connects a WDM transmitter and a WDM

receiver. Of the WDM transmitter, only a multiplexer 102 and an output erbium-doped

fiber amplifier (EDFA) 104 having gain G_A are depicted. Of the WDM receiver, only a

demultiplexer 106 and a receiver block 108 for a single WDM channel are depicted.

Further details of the WDM transmitter and WDM receiver are not germane to the present invention. Also, chromatic dispersion compensation components are omitted for ease of description and illustration.

5 In this example, there is no regeneration of the optical signal along the link. All amplification is purely optical. For the purpose of amplification, the link is divided into 25 spans. For ease of illustration, only a single span 110 is depicted. Typically, each of the spans incorporates similar components. In a particular example, each span represents 125 km of TW-RS™ fiber available from Lucent Technologies. Link 100 thus extends

10 for 3125 km. Link 100 carries 32 WDM channels spaced 50 GHz apart and centered at approximately 1545 nm. The dispersion of the fiber at this wavelength is D=4.18 ps/nm/km.

The fiber of each span introduces approximately 25 dB of loss. To compensate for this loss, each span incorporates an EDFA 112 having G_A. In one embodiment, G_A =

15 10 dB and EDFA 112 has a 7 dB noise figure. To provide the remaining needed compensation for span loss, (15 dB here) a Raman amplifier 113 is also included. Raman amplification is induced in a fiber 115 by use of both a co-propagating pump 114 and a counter-propagating pump 116. Pumps 114 and 116 are coupled into fiber 115 by couplers 118 and 120 respectively. The operation of co-propagating pump 114 gives rise

20 to a forward Raman gain, G_F, while the operation of counter-propagating pump 116 gives rise to a backward Raman gain, G_B. The pumps emit energy at 1445 nm

Methods and criteria for selecting G_F and G_B for optimal link operation will now be described. Performance criteria to be considered include signal to noise ratio, four-

wave mixing product suppression, double Rayleigh backscattering product suppression, cross-gain modulation due to amplifier saturation, etc.

Fig. 2 is a graph depicting the relationship between four-wave-mixing-induced cross-talk and forward Raman gain according to one embodiment of the present invention. The theoretical basis for the data determined in Fig. 2 may be found in U.S. Provisional App. No. 60/279,854, entitled INTERACTION OF FOUR-WAVE MIXING AND DISTRIBUTED RAMAN ARCHITECTURE and filed on March 28, 2001. Fig. 2 is a useful tool in selecting values for G_F and G_B. The x axis of the graph of Fig. 2

10   represents unsaturated forward Raman gain. The left y-scale of the graph of Fig. 2 represents input power per channel to fiber 115. The right y-scale of Fig. 2 reports the corresponding four-wave mixing-induced cross talk at the end of the whole link of 25 spans assuming that G_B provides the remainder of the 15 dB that G_F does not provide. To get this crosstalk, individual contributions from each span are added.

15   Fig. 2 assumes a dispersion value of D=4.185 ps/nm/km at the relevant wavelengths and an effective area, $A_{eff}= 55 \ \mu m^2$. The data points of Fig. 2 and the relationship between channel power and four-wave mixing product suppression assume that within the 15 dB gain budgeted for Raman amplifier 113, gain not provided by the operation of the co-propagating pump (G_F) is provided by the counter-propagating pump

20   (G_B). The four-wave mixing product has been computed according to:

$$X'_F = \frac{\left\langle \left(i_1 - \langle i_1 \rangle \right)^2 \right\rangle}{\langle i_1 \rangle^2}$$ where i_1 is the photodiode current corresponding to a received

"1" value.

In this example, it is assumed that 0.5 dB of gain saturation, i.e., saturation effects that cause a 0.5 dB loss of gain represents a maximum tolerable level of saturation for the Raman amplifier of each span. Above this limit, cross-gain modulation causes

5   intolerable transmission impairments in the example of Fig. 2. A dotted line represents a contour of gain/power combinations causing 0.5 dB of saturation. It is also assumed that adequate WDM receiver performance requires that the link achieve an 11 dB output optical signal to noise ratio (OSNR) as measured over a 0.5 nm bandwidth, taking into account noise introduced by all the amplifiers (both the 25 Raman amplifiers and the 26

10   EDFAs). The solid line is a contour representing combinations of forward gain and input power per channel that give rise to this desired OSNR at the output of Raman amplifier 113. The input power per channel is set by the EDFA preceding the Raman amplifier.

It will then be appreciated that the combination of forward Raman gain and channel power to be employed should be on the solid curve to achieve the desired OSNR

15   while maximizing suppression of four-wave mixing products. To maintain less than 0.5 dB of saturation, the selected gain/power combination should also be to the left of the dotted line curve. One example of a gain/power combination 202 that meets these criteria is a forward gain of approximately 5.50 dB in combination with a per-channel input power of approximately –5 dBm. It will be seen that this corresponds to a four-

20   wave mixing cross talk of approximately -31 dB. By contrast, if only the counter-propagating pump 116 were used (G_F=0), achieving the same gain and signal to noise ratio would mean a four-wave mixing product suppression level of only -24 dB, insufficient for correct WDM receiver operation. If only the counter-propagating pump (i.e. G_F=0) were used and the input channel power were set to achieve –31 dB of four-

wave mixing crosstalk, an OSNR of approximately only 7.5 dB would be obtained. It has

been found that forward gains of greater than 4 dB are often particularly advantageous in

suppressing four-wave mixing products and achieving good OSNR performance.

5   Once G_F has been selected, the backward gain G_B is selected by subtracting G_F

from the gain allocated to Raman amplifier 113, e.g., 15 dB in the depicted example. The

power level of pump 114 is adjusted empirically to achieve the desired G_F value and the

power level of pump 116 is adjusted empirically to achieve the desired G_B value.

Fig. 3 is a graph depicting the relationship between cross-gain modulation and

10   gain saturation over all 25 spans according to one embodiment of the present invention.

The graph assumes a typical distribution of chromatic dispersion and chromatic

dispersion compensation through the link. This graph further assumes that the pumps

emit energy at 1445 nm. Fig. 3 is presented to support the selection of 0.5 dB as a

desired maximum saturation level. It is seen that cross-gain modulation is suppressed by

15   30 dB for a gain saturation of 0.5 dB and power per channel of –5 dBm. This is deemed

to be sufficient suppression for typical WDM receiver operation.

Another important Raman amplifier impairment to control is double Rayleigh

backscattering. Fig. 4 is a graph depicting the relationship between double Rayleigh

back-scattering and Raman gain according to one embodiment of the present invention.

20   Fig. 4 assumes the use of TW-RS fiber, an effective area of 55 μm^2, a Rayleigh back-

scattering coefficient of 5.25x10-8 m^{-1}, a pump wavelength of 1445 nm, a signal

wavelength of 1545 nm.

Fig. 4 shows the Raman backscattering product caused by either the co–

propagating pump or counter-propagating pump. This product is computed using the

techniques disclosed in P.Hansen et al., *IEEE Photon. Tech. Lett.*, Vol.10, No.1 (1998), p. 159, the contents of which are herein incorporated by reference. To evaluate the backscattering product suppression for a given configuration of Raman amplifier 113, one separately determines the suppression levels for the forward and backward gains using the values given by Fig. 4 for the number of spans in the link. Then, the double Rayleigh back scattering noise levels contributed by the forward and backward gain are computed given the suppression levels and the signal level at the output level of Raman amplifier 113. These noise levels are added and compared to the signal level to obtain the double Rayleigh backscattering suppression level. In general, double Rayleigh backscattering suppression of greater than 30 dB is typically required. For our previous example system where G_F= 5.5 dB and G_B= 9.5 dB, the double Rayleigh backsckattering suppression is approximately 37.5 dB.

It will be appreciated that there are many combinations of forward gain and backward gain that will give rise to a system with adequate signal to noise ratio, four-wave mixing product suppression, double Rayleigh backscattering product suppression, cross-gain modulation product suppression, etc. The graphical methods described above are only one possible method of selecting forward and backward gain for Raman amplifier 113 according to the invention. Alternatively, one could select a combination of forward gain and backward gain based on a desired double backscattering product suppression level, four wave mixing product suppression level, and signal to noise ratio and then verify the gain saturation performance that would result from the selected gains. By employing both co-propagating and counter-propagating pump energy, Raman amplifier 113 achieves combinations of output signal to noise ratio and four-wave mixing

product suppression that cannot be achieved using only counter-propagating optical energy.

It is understood that the examples and embodiments that are described herein are for illustrative purposes only and that various modifications and changes in light thereof will be suggested to persons skilled in the art and are to be included within the spirit and purview of this application and scope of the appended claims and their full scope of equivalents. For example, other optical components may be included between components shown as being directly connected in Fig. 1.

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